A method to bridge the gap between affordance formalisation and visual simulation in virtual environment

(Short title : Affordance Modelling and Simulation)

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Abstract

Recently, Wells (2002) suggested using the formalism of the Turing Machine to describe the concept of affordance. Even though the author has shown that the generic properties of the concept were taken into account in this modelling, no research has yet attempted to model adaptive behaviour in an ecosystem with this formalism. In this paper, we propose to facilitate the passage from an abstract model of affordance through the Turing Machine to a concrete simulation of the model within a Virtual Environment. This simulation makes the direct observation of the emergence of interaction between a human or animal agent and some relevant patterns of sensorial information coming from the surroundings (sensorial invariants) possible.

After a presentation of the different stages of the modelling method, we illustrate it by applying it to a basic ecological situation: the predation behaviour of the tick (*Ixodes Ricinus*). This modelling effort enables us to envisage the potentialities, the limits and the issues of this framework.

Key-words: affordance, modelling method, Turing Machine, Virtual Reality, tick.

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Introduction

The concept of affordance emerged from the research of ecological psychologist J. J. Gibson. This concept took on a crucial dimension in the work of the author, (Gibson, 1979) and afterwards in ecological psychology. The reason for the central position of this concept can be found in the fact that it symbolizes Gibson's radical theoretical position as opposed to the cognitive approach found in psychology. While the cognitive approach dissociates the subject and the environment, focusing its interest on the individual internal stages of information processing, the ecological approach proposed by Gibson suggests a continuum between individual subjectivity and the objective environment. This continuum allows for the adaptation of animals to their ecological niche without triggering symbolic internal information processing, enclosing the subject in its subjectivity.

However, it is clear for anyone working on the concept of affordance that the "non-initiated reader" encounters difficulties in grasping it. Even among researchers, the notion of affordance always incites debates as to its correct and explicit definition (see for instance, Stoffregen, 2004). Certainly the difficulty of its conceptual meaning can be partly found in the fact that "affordance" is a neologism coming from the verb "to afford", but without any reference to an actual entity corresponding to a physical, biological or cognitive object. Instead, this concept concerns the relationship between one or several environmental properties and one or several animals within the framework of certain adaptive needs. As an example, a plane and resistant surface provides a space for locomotion for terrestrial animals, whilst this same surface provides a landing space for flying animals. This substantive notion is inherently relative to a given situation of interaction between an animal and an environment. In other words, the same object changes its ecological meaning or functional identity according to the animal involved and its state.

This relativism specifying the notion of affordance hardly deals with an accurate literal definition of it. The definition that best fits with this relativism should be rather of the mathematical kind: a mathematical function depending on several variables concerning an environment and an animal.

Several works have tried to formalise the concept of affordance. Firstly, Warren (1984) proposed a mathematical equation of affordance on the basis of experimental designs. This research opened the experimental exploration of some other affordances, such as the relation between a doorway aperture and the participants' shoulder widths (Warren & Whang, 1987). Another mathematical investigation of affordance came from the works of Shaw and Turvey (1981) through their theory which considers an ecosystem as being composed of an animal and its surroundings. Later, Turvey (1992) developed a personal formalisation of affordances as emergent properties coming from a couple of entities: respectively, an object's property relevant for an animal and the capacity of action of this animal, which has been called "effectivity" since the works of Shaw and Turvey (1981). For instance, this couple could consist of a ball with its diameter property and as effectivity, the paw of an animal with its prehensile span. One of us participated in elaborating a model of affordances within the framework of the design for industrial software (Morineau, Chedmail, and Parenthoën, 2001) and the analysis of sailor activity in designing an automatic pilot system (Parenthoën, Tisseau, & Morineau, 2002). This modelling was close to the Wells proposal (2002), but without having obtained the same high degree of formalisation. Recently, Wells (2002) proposed using the works of Alan Turing (1936-1937), one of the fathers of modern Computer Sciences, to describe the concept of affordance. Wells envisages Turing's computational theory as having the capability to describe the ecological interaction between an agent and its surroundings (Wells, 1998). As we will see further on, Wells showed that Turing Machine formalism makes it possible to explain the meaning of affordance through a set of definite features.

But, all these formal studies on the concept of affordance do not privilege a straightforward evaluation of their qualities in a more complex world than the experimental design of a passage through a door. From our point of view, affordance modelling in a real complex world requires the observation of the multiple relational properties emerging at the time of an interaction between at least an animal and its natural environment. Indeed, the core of the affordance definition resides in the display of the emergent relational properties between an agent and its surrounding. And paradoxically, a classical cognitivist criticism of the ecological approach of cognition underlines the lack of computational simulation of theoretical models that would permit such a display of emergent relational properties (Simon & Gobet, 2000). So, our purpose is to propose a method to bridge the gap between a formal modelling of affordance and a visual simulation of this modelling in a virtual environment.

In the following section, we present Wells' proposal for affordance modelling with the Turing Machine and rationales demonstrating that the configurations of a Turing Machine correctly describe formal properties of affordances. In section 3, we elicit the stages of a method to elaborate a Turing Machine analysis of affordances and consequently the implementation of this analysis through a virtual environment. Section 4 describes the application of our method on an elementary ecological situation: the predation behaviour of the tick called *Ixodes Ricinus.* In conclusion, we present the consequences of the tick's virtual environment modelling.

2. Affordance modelling with the Turing computational theory: the Wells proposal (2002).

Wells proposed reconsidering the two main points implied in the affordance concept. These two points are, respectively, external information coming from the environment and animal activity relative to this information (effectivity). Then he suggested modelling their interactions, from which affordances emerge.

2.1. The Turing Machine

For his purpose of demonstrating the calculability (or decidability) of a number, Turing looked for a very general calculus procedure that makes it possible to deal with any kind of mathematical object (number, function, predicate). The general character of this procedure implies that it involves sufficient elementary operations to be applicable to many kinds of objects. In the second instance, this elementary aspect of operations implies that a machine works without the help of human cognitive ability.

To define the features of such a machine, Turing described in his article (1936-1937/1995) the limited means needed for a human being to carry out a calculus. This description has been the basis upon which Wells founded an analogy with the concept of affordance.

Turing notes that every calculus can be performed with the help of a paper tape composed of an infinite number of squares. In each square, the calculator agent is able to write a symbol chosen from a finite set of symbols, for example *{0, 1, #}*. At any time, the action of the calculator agent is a consequence of the symbols observed on the paper tape and of its “mental state”. Like the symbol number, the number of possible mental states is finite. Each action of the calculator agent is composed of a sequence of elementary operations. Each elementary operation modifies the system that is made by the agent and of the paper tape on the scale of a given square. The elementary operations can be:

1. Read the symbol in the observed square;
2. Replace the symbol read in the observed square;
3. Move the tape to the left or the right side, to the next square;
4. Symbol change or tape moving may be carried out simultaneously through a change in the mental state of the agent.

Also, Turing emphasised that it is the mental state of the calculator and the symbols observed that determine the operation to perform and in particular the next mental state of the agent after the execution of the operation in question. In this way, we can consider agent behaviour as being linked to the interaction between the agent and information coming from the environment (in Turing’s case, the symbols on the paper tape).

Now, in order to describe the description of Turing Machine formalism and the results provided by “mental state/environment state” interaction, the notions of “configuration” and “machine table” are introduced. A configuration corresponds to a value of the couple (mental state, environmental state) and a machine table is a two-entry table showing the action performed by the agent for each configuration. For instance, in a given configuration named *c*, the agent is in state *q* and the inspected square contains the symbol *s*. This configuration could, for example, generate the following action: the agent writes the symbol *1*, moves to mental state *q2* and then takes position in the next square to the right.

Partly on the basis proposed by Wells, we shall use the following notation: the agent is modelled by a set of states $Q=\{q1, q2,\ldots\}$ and the environment by a set of situations $S=\{s1, s2,\ldots\}$. The set of possible configurations is also a set of couples $A=\{a=(s,q), s \in S, q \in Q\}$. An action via the machine table is associated with each value of the couple $a=(s,q)$, that is to say, an ordered triplet of operations $(b, \underline{q}, k)$. Operation b, chosen from a set $B=\{b1,b2,\ldots\}$, describes how the agent transforms the environment. Operation $\underline{q} \in \underline{Q}=\{\underline{q}1, \underline{q}2, \ldots\}$ gives the change of the agent's mental state with the convention that $\underline{q}1$ means "move to state q1" and so on. $k \in K=\{k1, k2, \ldots\}$ is related to the movement of the agent in the environment.

Through a configuration table, the behaviour of an agent is entirely determined and anticipated by the configurations described in the table. This is the deterministic method (Dehornoy, 1993). It involves a sequence of discrete (non-continuous) elementary stages that imply a finite set of parameters (the behaviour of the Turing Machine). However, it must be noted that we could envisage a non-deterministic method when the agent reaches an ambiguous configuration. In this case, an external operator could intervene and make a choice for pursuing the process.

2.2. Affordance and Turing Machine configurations

Wells (2002) used the notion of configuration described above to explain the interaction between an animal with a given mental state, and information coming from the environmental situation. He shows that the main features constituting the affordance concept are present in the Turing machine model. Firstly, if the non-limited number of squares on the paper tape and the non-limited operating time is considered as acceptable, the Turing Machine contributes to the description of a human behaviour consisting of writing symbols on paper with a pencil. The second reason consists of the possibility of depicting a system of perception-action control in an environment. Furthermore, these configurations are also relational concepts. They model the interaction between mental states and environmental information and the result of this interaction, which can consequently modify a mental state. Finally, the notions of the elementary operation of symbol reading and moving would give quite a good account of the central aspect of direct perception for animals.

Nonetheless, the application of Turing Machine formalism was limited to the example of the HP prisoner, who must write the sequence of integer numbers on a paper tape with an infinite dimension and with infinite time to perform the task. In order to go further in testing the interest of this formalism, it is necessary to have methodological tools to apply this model to a variety of ecological niches.

3. A methodological proposal to implement a simulation of a Turing Machine affordance modelling

The development of a theoretical field depends on the methodological means available for the proof of its validity. So, we propose a methodological framework to build virtual environments easily that will forward the rendering of hypotheses on the affordances in a specific ecosystem. These hypotheses could emerge from insight, deductive reasoning or ethological observations made by a researcher. The virtual simulation gives the advantage of making observations without interfering with the ecosystem and potentially, rapidly testing a large set of hypotheses and their interactions.

Our methodological proposal is inspired by methodological research done in ecological psychology applied to cognitive engineering. The research done by Vicente & Rasmussen (1990) led to the development of a methodological framework that made it possible to carry out serious advancement in the study of man-machine interaction in complex systems: The Cognitive Work Analysis framework (CWA – Vicente, 1999). The power of this methodological framework can be emphasised, respectively, by the number of different domains on which this methodology has been applied in order to design Ecological Interface based on CWA, and by the fact that several researchers converge towards the same methodological approach of study on man-machine interaction (Potter, Elm, Roth, Gualtieri, & Easter, 2002). From this ecological ergonomics research, we extracted the stages of a general method modelling affordances. This method could be used to model animal behaviours as well as human behaviours based on skills in which affordances are critical to the triggering of adaptive behaviour as in the work domain. Before showing how to apply our method to a specific case (tick predation behaviour), we will present the 6 stages of our methodology.

Stage 1 of the method: Functional representation of the ecosystem

Generally, the ecological approach proposes that the relevant unit of study is not the environment or the individual in such, but the interaction between them. The notion of ecosystem clearly represents this purpose: an ecosystem is an environment in which an agent lives, articulating the objective features of the system and the viewpoint of the animal considered. In cognitive engineering, this notion is called "domain" and corresponds to the constraints and purposes furnished by the work system to the human agent in his/her activity. The functional representation of the ecosystem privileges highlighting the functions linking a set of states and changes in the environments to the possibilities of perception and action of the agent. This representation involves expert knowledge on the objects and rules governing the ecosystem or domain from the viewpoint of the agent. A general functional hierarchy of the adaptive animal's needs has been proposed by ethologists (Tinbergen, 1951) and by cognitive engineering researchers Rasmussen & Vicente (1990). Note that particularly in the case of natural ecosystems that are large opened systems, the functional representation requires the accurate marking off of the ecosystem parts modelled.

Stage 2 of the method: Behavioural sequence of the agent

While adaptive purposes in a work domain are those defined by the work organisation, task and constraints posed by the object on which the operator works, like keeping a balance between mass and energy in a nuclear plant (Vicente, 1999), in a natural ecosystem a lot of pathways are available for the agent to reach the general adaptive purposes. In a natural setting, the purposes consist in satisfying general needs for the adaptation of the animal, the satisfaction of its psycho-physiological needs. These adaptive needs like predation or mating are innate or acquired as the function of the species. Thus, it constitutes rigid or flexible adaptive behaviour. When the behaviour is acquired by imitation, practice or learning, some degrees of freedom are given to the individual who can select behaviour in function to the situation in which he/she is living.

This second stage requires defining the purposes and pathways that the agent follows in its behaviour. This definition takes into account, respectively, the functional expert analysis of the agent's ecosystem, previously made and a discrete decomposition of the behaviour observed in a sequence through goals and stages on the basis of an interpretation of the course of the action. The definition of the behavioural sequence in this second stage of the method makes disposing of the first basis that shall be used to determine the mental states of the Turing Machine modelling the affordances concerned possible.

Stage 3 of the method: Relevant patterns of sensorial information

Generally, goals and sub-goals that the agent intends to reach during its behaviour are based on action-perception cycles which encode sensorial information (except in the case of feed-forward behaviours which are directed by an internal mental model in a complex decision process or when the action is very fast – ballistic action). This sensorial information perceived constitutes feedback triggering the search for new action bringing the agent nearer to its adaptive general purpose (Flach, 1999). A pathway across the goals and sub-goals can be sometimes strongly embedded. For instance, the German physiologist Von Uexküll (1956) described the case of a female grasshopper enclosed in a transparent bell and emitting a cry retransmitted in another place by an experimental microphone. The males will approach the area where the cry is emitted, but will neglect the female, even though she is quite visible. Thus the behaviour of the male grasshopper depends on reaching certain patterns of sensorial information to attain another higher goal (the female), even though this higher goal is directly visible. Even if the human being is generally less dependant on the perception of external sensorial information triggering behaviour, research has shown that the human being can be submitted to priming effect of cues in skill-based behaviour. For instance in a high-skilled activity like Air Traffic Control, the controllers run their monitoring activity with patterns of information coming from events triggering specific action. And the controllers do not seem to be aware of this triggering process (Morineau, Hoc & Denecker, 2003). The difference between a human acquired triggered behaviour and an insect innate triggered behaviour inheres in the fact that the insect is strictly dependent on a pattern of information to pursue its behaviour, whilst the human being can adapt his/her strategy and figure out another course of action and inhibits sensory information triggering.

Contrary to the academic example of the Wells (2002) HP prisoner who encodes one elementary symbol in the set composed of 0, 1 or #, ecological relevant information for one stage in a natural behaviour sequence is rarely unique and rarely depends on just one sensorial modality. As Gibson (1982) pointed out, the agent picks up a sensorial array. Some arrays are selected by adaptation as ecological relevant information specific to the organism interacting with its ecological niche. Animals tend to ignore properties that are irrelevant to their needs at one given moment, and their perceptual system is structured to detect information central to these needs (McCabe, 1982). A sensorial invariant is not a physical property or object perceived in a realistic way from an exo-centred point of view. An invariant takes into account the environmental information and the animal characteristics (body and sensory-motor mechanisms). The existence of sensorial invariants which drive a behaviour sequence can be demonstrated by the technique of lure classically used in Ethology to elicit the critical patterns of information (Tinbergen, 1951).

Moreover, the notion of sensory pattern of information (or sensorial invariant) is in accordance with recent physiological research showing that the animal central nervous system is particularly implied in the integration of multiple inter-sensory information. This fact has been noted in the different cases of many species, such as Humans, monkeys, cats, (Driver & Spence, 2000; Lovelace & Partan, 2001), but also in the arthropod category including insects and acarina (Strausfeld, Hansen, Li, Gomez, & Ito, 1998).

At this stage of the method, the elicitation of each sensory pattern of information simply requires the defining of the set of relevant sensorial invariants for each stage of the target behavioural sequence. Note that the sensorial invariants form pre-structured input information of the Turing Machine Modelling given by the researcher. So, the resulting model will not include the simulation of sensorial invariants elaboration *per se* through perceptual processes.

Stage 4 of the method: Triggering of operations and action schemes

At this level of affordance modelling, we have at hand, respectively, a functional description of the agent and its ecosystem, a behavioural sequence depicting as well as the patterns of sensorial information relevant for each stage of this sequence. Now, the operations triggered by the sensory patterns of information for each behavioural stage must be considered. But firstly, let us recall that Turing Machine formalism classifies operations under three kinds of elements: transformation (the agent writes information into its environment; it transforms its surrounding), change of state (the agent progresses in its behavioural sequence), and action (the agent performs an action, that is to say limb movement or body locomotion). For each interaction between a behavioural stage and a pattern of sensorial information, we have to consider whether a transformation, a change of state, or an action has been performed by the agent. This modelling is the more difficult stage of the Turing Machine elaboration process. Firstly, the researcher must define the sets of transformation and action schemes that the agent is able to perform. The transformation and the action are qualified as a “scheme”, that is to say generic motor programs like “moving”, “sticking”, “grasping”. The level of abstraction depends on the researcher’s focus. But note that as sensorial invariants perception processes, motor programs are not modelled in the Turing Machine simulation. Once the set of operations is defined, two requirements must be made. Firstly, consider that there is *n* relevant sensory information in a unique pattern of information and having the possible values of 1 or 0 as the function of its presence or lack of it in the pattern, then we must envisage 2^n possible sensory information patterns that the agent could perceive. Each pattern engages its own set of operations. This mapping between patterns of sensory information and operations shall help respect the exclusive character of entities read on the tape (i.e. information perceived in the surrounding by the agent) required by the functioning of the Turing Machine. Secondly, the mapping between behavioural sequence stages, sensorial invariants and operations must lead the researcher to redefine the behavioural stages in order to transform these stages into a number of Turing Machine mental states necessary and sufficient to run the Turing Machine. This requirement leads to the next stage of the method.

Stage 5 of the method: Mental states of the Turing Machine

On the base of iterative logical refinement of the behaviour sequence, the statement of the Turing Machine mental states constitutes the fullfilment of the necessary and sufficient steps by which the agent must pass in order to process the sensorial patterns of information and achieve the adaptive goal driving the behaviour. Thus, the final number of mental states elicited by the model can be different from the first description of the behaviour sequence made up on the base of expert knowledge of the animal or human. The Turing Machine mental states correspond to the logical requirements for information processing without representing behavioural interpretation made by an observer. The comparison between the first expert definition of the behavioural sequence and the number of mental states emerging from the Turing Machine can serve to highlight some issues, like the possible dependency of the expert observation from behavioural appearing changes which do not constitute changes for the animal or also, the possible antropomorphism implied in the behaviour observation, which always constitutes a risk in Behaviour Science (Timberlake, 1997 ; Von Uexküll, 1957).

Stage 6 of the method: Implementation in virtual environment

This last stage of our method gives the opportunity of making the Turing Machine visible through the implementation in a Virtual Environment. This stage is clearly important if the researcher wants to observe directly the effect of multiple variables on the emergent behaviour. Once an agent is implemented in a world and the ecological variables are included in the external sensory information patterns relevant for this agent, the researcher can easily copy the agent and the ecological relevant properties to observe several agents in a same environment and effects of changing variables.

The programing of the Turing Machine can be easily done with a classical computer language, where functions like “if...then...else” rules and “while” loop are available. Table 6 shows the logical structure of such a Turing Machine program. The program is embedded in a “While” loop corresponding to the reaching of the final state (*H*), that pushes the modelled behaviour forward. The second level in this loop is composed of rules with as condition the state in which the agent stands. At the third level, we can find other rules, with as condition the patterns of sensory information encoded by the agent, that is to say the ecological zone in which the agent is in the virtual environment. These rules activate the set of operations required by the Turing Machine: possible transformation (here, penetration), change of state and action like dropping, moving, stopping, etc. Graphically, the researcher can see the adaptive behaviour in an ecosystem of which the characteristics can be modified like the position of the agent pertaining to the different patterns of sensory information or ecological zones. Note that the exhaustive process of all sensory information patterns that could be picked up by the agent insures the display of a reliable behaviour of the agent modelled, whatever the properties of the virtual environment in which the agent is. Thus through this work, we make a methodological tool to model and simulate affordance in an ecological niche available to researchers in behaviour science .

4. An application of the Turing Machine affordance modelling: the predation behaviour of the tick *Ixodes Ricinus*

The choice of tick predation is justified by the elementary character of this behaviour, facilitating the presentation of the course of our method. Moreover, this animal sequence has been used by Von Uexküll (1957) to illustrate his theory of natural composition, which is similar in several points to the theory of affordance. The tick’s ecosystem is described first.

4.1. The Ixodes Ricinus life in its ecosystem

Ticks are large-sized acarina (2 to 30 mm) which have not evolved for 400 million years. Currently, approximately 850 species are known and are divided into three families: the *Ixodidae* or hard tick, the *Argasidae* or soft tick and the *Nutalliellidae* which comprises only a single species. Ticks feed on blood, and are important vectors of disease (Mejlon, 2000). We focused our modelling on a hard tick called *Ixodes Ricinus,* which lives in Western Europe. To understand the world in which the tick lives from its own point of view, it is necessary to describe its perceptual and motor possibilities. It constitutes the tick’s link with the external world shaping its own representation of the surrounding, or in other words its *Umwelt* (Von Uexküll, 1957).

From a movement point of view, *Ixodae* have 6 legs at the larva stage and reach 8 legs at the nymph and adult stages. These legs are provided with hooks and suction cups. The hooks allow fixing on rough objects and surfaces, whilst the suction cups are for adhering to the plane surface in particular the host's skin. A tick does not really have a mouth. Its oral organ consists of a beak (chelicerae) with which it perforates the skin of animals and nourishes itself with blood

As for sensorial information, the *Ixodes Ricinus* is blind because it has no eyes. The sense organs involved in tick feeding behaviour are concentrated at the anterior end of the body, in three locations – on the first pairs of legs; on the palps; and in the chelicerae. The tick carries the Haller's organ on the first pair of legs. This sensitive sensor includes olfactory chemoreceptors, gustatory receptors, mechanoreceptors (touch), and heat receptors. The palpal receptors have gustatory and olfactory functions. The cheliceral receptors (the mouthpart) are mainly gustatory and mechanoreceptive (Wallade & Rice, 1982). The tick uses these sensors while exploring a host body but also to detect the approach of a potential host through odour (acid ascorbic emitted by sweat and lactic acid). The tick can also detect mechanical vibrations transmitted by the ground and CO2 emanating at a distance from the target animal (Osterkamp, Wahl, Schamalfuss & Haas, 1999). Table 1 points out the functional features of I. Ricinus that we retained in our modelling of feeding behaviour.

As every *Ixodidae* species, the *I. Ricinus* takes only three blood meals, each one on a particular host. Each instar (larva, nymph, and adult) has to find its own individual host. Entomologists found that the *Ixodes Ricinus* species can feed on a large range of vertebrate hosts including mammals, birds and reptiles. But small mammals (like shrews or voles) are usually the main hosts for *I. Ricinus* larvae and a small proportion of nymphs, whilst adult female ticks feed on larger host animals such as hares or roe deer. The segment of tick hosts that can undergo feeding by female ticks is defined as maintenance hosts. These variations in animal targets also depend on variations in the specific ecosystem in which the tick lives (Mejlon, 2000).

4.2. Feeding behaviour sequence of the *Ixodes Ricinus*

It is interesting to note that if we refer to the most expert accurate behaviour analysis we found in the published research (Wallade & Rice, 1982), their chapter entitled the *"Sensory basis of tick feeding behaviour"* shows that firstly they claim that this feeding behaviour is a complexity of processes integrated *"into a single, meaningful function which we can artificially resolve by Tinbergian analysis into a sequence of nine main events. These events can be identified by familiar terms, most of which have been used before with a variety of meanings."* (p. 72). This statement highlights the artificial character of a sequence decomposition made by observation analysis. Moreover, this observation is impeded by anthropomorphic terms that refer to personal definitions of behaviour aspects. The translation of such an artificial decomposition into Turing Machine mental states logically requires that the performing of the behaviour helps to go past these limitations.

In the case of the tick feeding behaviour, Wallade & Rice (1982) suggests the nine following main events in the behaviour sequence: Appetence (the tick waits for its prey), Engagement (the tick goes on its prey), Exploration (the tick moves on the skin of its host), Penetration (the beak of the tick penetrates the host's skin), Attachment (the tick is fixed on the host), Ingestion (the tick ingests the blood), Engorgement (the tick feeds), Detachment (the tick detaches itself from the host), Disengagement (the tick leaves the host). But they regroup these events in their chapter as following: Host location (Appetence and Engagement), Attachment (exploration, penetration, and attachment), Engorgement (engorgement, detachment, and disengagement). On the base of the knowledge gathered on the tick feeding, we chose to describe the Ixodes Ricinus female feeding behaviour through these three wide-ranged events:

Host location

The first stage consists in waiting for a host (questing, appetence). The tick crawls up blades of grass or perches on the edges of leaves on the ground in a typical posture with its front legs extended, especially in response to a host passing by. Two different strategies exist during questing. If the prey is rather large and nearby, the tick will grasp it, whatever the nature of the tactile information collected by the sensory receivers on the legs. The second strategy during questing is whether the tick detects a host at a distance, then it will drop down. To anticipate the presence of the host, the tick has two main kinds of distance sensory information: odour and vibration. Entomologists suppose that odour is the key downwind stimulus, whilst vibration is the key upwind stimulus to promote engagement. Note that the strategy of grasping is more randomised in the frame of the correct identification of the prey, since the tick grasps whatever surface or object with which it comes into contact. On the other hand, the strategy of the fall is more randomised in the field of the result of the action: falling at the right place and right time.

Attachment

Before pricking, a tick may inspect the selected animal for several hours. The exploration of the host consists in finding a part of warm surface (skin) where it can reach blood. During exploration, the tick can find an obstacle stopping its moving, surface requiring only gripping with hooks, or surface where suction cups can insure stability and the possibility that this surface is skin. Naturally, the tick does not know that it is standing on a mammal, a reptile, a stone or on the earth. After dropping or grasping the thing that came close to it, the tick detects some sensorial information triggering a specific behaviour in its repertoire. If the tick feels a surface through its suction cups, which is warm in the context of lactic or ascorbic acid odour, then the questing will be considered a success, allowing the transition to the next stage of feeding.

Consider that our female tick looks to feed on a mammal. Two pieces of critical sensory information must be underlined at this stage of the tick’s behaviour: a surface which is warm and penetrable enough for its mouthpart. Once the tick finds a part of tender skin where it can reach warm blood (for example, the neck), its inserts its mouthpart.

Engorgement

The tick will suck the blood of a host for several days (6 to 10 days). During this time, the body of the tick increases until it forms a small sphere. After the meal, the tick leaves the host and drops to the ground to digest the blood and transform into the next developmental stage (larva, nymph or adult), or if it is an adult female, to lay its eggs. Note that the male does not require blood as an adult, but spends its time in search of females.

4.3. Relevant patterns of sensorial information for tick feeding

We have selected the invariants necessary for the fulfilment of one stage in the tick predation. The tick is embedded in multiple sensory information. For instance, when the tick is on a mammal, it feels the odour, the heat, the sticking surface of the skin and maybe a grippable object or an obstacle in front of it. Finally, we define sensorial invariants as following:

The symbol $s \in S=\{s1, s2, \ldots, s56\}$ relates to patterns of environmental information perceptible by the animal. A pattern *s* of sensory information consists of a set of sensory information $e \in E=\{e1, e2, \ldots, e8\}$*, where e1 is "vibration", e2 is "odour", e3 is "obstacle", e4 is "grippable object", e5 is "sticking surface", e6 is "warm surface", e7 is "penetrable surface" and e8 is "blood".* For instance, the presence of an obstacle is defined by taking into account the features of the environmental area in front of the tick and the impossibility for the tick to implement an action scheme of gripping or sticking on this environmental area.

4.4. Triggering of operations and action schemes for tick feeding

In a first step, we have defined the set of operations available for the *I. Ricinus* tick. (transformation schemes of its surrounding, state changing and action schemes). We call *O* the set of operations that describes tick activity. This set is made up of triplets *(b, q, k)*, considering that it:

b: corresponds to animal transformations on the environment. In the Turing Machine formalism, it means that the agent writes a new symbol on the paper tape. Consider the paper tapes as the environment perceived by the agent (its sensorial register), it means that the direct action of the agent produces new perceptual information which did not exist in its surrounding before. In the tick predation sequence, it is the case when it penetrates the skin of the host. But note that contrary to the artificial agent which is ensured to write a new symbol on the paper tape at the same level of probability of reading a symbol, the probability for a natural agent to succeed in producing an environmental transformation is less than the picking up of a sensorial information already available.

The animal tries to transform the environment that is to say to penetrate the skin. Afterwards it will read the presence or lack thereof of this transformation on its sensorial register.

So, the application of the Turing Machine formalism on the simulation of an ecological situation lead us to modify the Turing Machine formalism slightly by considering that any action of writing "on the paper tape" on behalf of the agent is an attempt which will only have dubious results. To differentiate this type of transformation from those classically accepted in Turing Machine formalism, we indicate that it is an attempt at transformation by putting the symbol, written between brackets, in the Machine Table. But in many configurations, the tick may not write any information on the host's body. Then the value of *b* is "empty set".

q: corresponds to the states to which the animal switches to at the time of experiencing a given affordance *(s,q)*, with the convention that *q1* means *"move to state q1"* and so on.

k: corresponds to the action scheme of the animal with its anterior legs, that we suppose as dominant in the movements *vis-à-vis* its posterior legs. An action scheme is driven by anterior legs, which triggers a motor program implementing one of the 7 following movements:

- *Preparing*: the animal stands on a surface with its front legs extended, looking for a place to touch or a drop onto.
- *Sticking*: the animal put its suction cups of its forefeet on a surface. We suppose that the biological evolution of the tick species particularly leads to adapt suction cups to the skin surface of a host.
- *Gripping*: the animal put the hooks of its forefeet on an object. We suppose that this object can be a part of a host where sticking cannot be used like on a hair.
- *Dropping*: The tick can drop from the place it is due to the base of some sensorial information, like a mammal odour or some information leading to giving up the host.
- *Rotating*: The front legs of the tick can induce a rotation, for instance, to avoid an obstacle detected by its front sensillae.
- *Moving*: This scheme corresponds to the locomotion of the tick, whatever its manner of laying on the surface (gripping or sticking).
- *Stopping* : The animal stops

4.5. Mental states of the Turing Machine and affordance for tick feeding behaviour

The iterative matching between the behaviour stages of the tick used as basis for mental states of the Turing Machine, the patterns of sensory information and the possible operations lead to the definition of a final Turing Machine representing the *I. Ricinus* tick affordance during feeding (tables 2-5). We thus call *A* the set of affordances for the tick. This set consists of the Turing Machine configurations, that is to say the couples $a=(s, q)$. The symbol $q \in Q=\{q1, q2, q3, q4, H\}$ represents the animal states. In our model, we take into account five states: *q1:questing, q2:exploration, q3:penetration, q4:nutrition*. The fifth state is a process-end state (*H*). Note that the names given to the four states are just post-hoc interpretations proposed after the logical emergence of the states during the Turing Machine elaboration.

INSERT TABLES 2-5

To understand the semantic involved in this Machine Table, we must describe the process of sensory integration of multiple information. On the base of adaptive criteria corresponding to the shortest way in accessing the behaviour goal of blood feeding, we adopted some priority rules in the selection of sensorial information in a pattern. The priorities between sensorial information in one pattern are the following for each animal state:

q1-questing.

Here, two strategies of questing have been modelled. From a sensory-motor point of view, the perception of a sticking surface is the main information making getting closer to a surface corresponding to a host’s skin possible. Even though the animal senses a mammal odour or vibration in parallel with the touch of a sticking surface with its forefeet, it seems better to stick to the surface than trying a hazardous drop. So, the patterns of information where the presence of a sticking surface is detected lead the tick to the scheme of sticking (*s2, s6, s7, s8, s9, s10, s14, s16, s22, s23, s24, s25, s26, s30, s32*). The second level of sensorial priority concerns the second tactile information that is gripping an object (*s3, s11, s13, s15, s19, s27, s29, s31*). In this situation, the tick will grip the object, with the expectation that this object is a part of the host (like a hair). Thirdly, the odour and vibration information are cues triggering a specific scheme (dropping). This situation can occur in the case of a small mammal that goes under the tick, without touching it (*s5, s12, s17, s20, s21, s28*). Finally, if there is no odour, no vibration or no tactile information, then the tick stays for questing (*s1 & s4*).

q2- exploration

In this state, the animal copes with the same critical sensorial information for its adaptation as during the first state of questing (except the vibration which was previously transmitted by the ground). But, the adaptive meanings of this persistent information and the rules of priority between them change significantly. The presence or lack of the mammal odour dominates as the rule to trigger the tick's behaviour. If this information is present, then the tick is certainly on a mammal and the exploration has to begin. In the other case, the tick is on a type of prey that is not a mammal and that has to be left, or the tick is already on the ground (*s33, s34, s35, s36, s38, s39, s41, s47*). In both cases, the tick has to move to the final state *H*. Note the importance of the lack of detection of certain sensorial information in the implementing of the behaviour. The second level of sensorial priority concerns the presence of or lack of an obstacle. In the context of a mammal odour, we consider that the presence of an obstacle induces the necessity of a rotation in order to find a good place for pursuing the exploration and testing the surface on which the tick is (*s44, s45, s46, s48*). The next level of priority relies on the discover of a sticking surface that means the possible presence of mammal skin under the legs of the tick. This situation leads the animal to shift its internal state, so it stops. (*s40, s42*). The fourth level of priority between sensory information is about information allowing the gripping scheme. In this case, the animal is on an object, which necessitates an exploration (moving) to search for a sticking surface (*s43, s45)*. For instance, this situation can occur whether the tick touches human clothes. Finally, note the specific situation where the tick detects an odour but no obstacle, no gripping or sticking surface (*s37*). In this case, we think that the tick is in a critical situation, having to move in order to find an anchor point for its body and to avoid falling.

q3 – penetration

The reaching of this state by the tick requires the standing of the animal on a surface (sticking). The sensorial information, that is relevant at this stage of the behaviour sequence changes from the previous stages. This state comes into the context of a mammal odour and a sticking surface (see state *q2*), then the tick must assess the nature of the surface in order to appreciate the possibility to bore it for finding blood. Thus, the tick perceives the heat of the surface to find a warm surface. The first rule is that if the surface is not warm, then the tick must re-explore the area and so returns to state *q2* (*s49, s50*). In the context of a warm surface, the animal tests the penetrableness of the surface. If the term "penetrable" is not written, then the tick stops, goes to state *q4* and attempts to write the term "penetrable" on the surface with the help of its beak (*s51*). This test consists in trying to make small holes in the host's skin. The result of this action may transform or not the external environment. We then choose to model this by the notion of "attempt at writing". If the term "penetrable" is already written (for instance, it is a wound), then the tick stops and goes to state *q4* (*s52*). The configuration where some invariants lead the tick to engage an attempt of penetration behaviour explains the possibility to gull the animal. In these two latter patterns of sensory information, the tick shifts from state *q3* to state *q4*.

q4 – nutrition

In this last state *q4*, if a small hole has been made in the host's skin, or in other words if the term "penetrable" has been written, the tick tries to find blood or in other words, is able to read the term "blood" if it is present. The optimal case is when the tick finds blood *(s56).* If the tick does not find blood, then it changes area by moving (*s55*). Finally, if the surface is not sufficiently penetrable to engage its beak, the tick cannot try to find blood and then moves (*s53*, *s54*). Here, we make a strong hypothesis: the blood meal of the tick is necessarily triggered by a sufficient penetration of the beak. If the tick abruptly finds blood without penetration, it does not feed on it. This hypothesis is coherent with the fact that the female tick has only one meal, which must be sufficiently important to allow the laying of its eggs. Only the significant penetration of a host can provide the necessary quantity of blood. In order to end the Turing Machine description, it has to be noticed that the time interval between two sequences of "reading-action" experienced a large variance. It amounts to only a few seconds in *q1* state but for a few days in *q4* state when the tick takes its meal.

These 4 mental states emerging from our modelling shows that the behavioural categorisation made originally by Wallade & Rice (1982) can be thought of in another way (five states instead of nine states).

4.6. The tick feeding behaviour simulated in Virtual Environment

The computational definition of the affordance gives us the original possibility to test the well-functioning of our model via an implementation. But, allowing the use of this kind of modelling tool by researchers in Behavioural Science requires that the model can be quite easily implemented, facilitating the reading of the results. It is the reason why we have chosen to implement the Tick's Turing Machine with a straightforward software of Virtual Reality programming, called ALICE, proposed by the research group Stage3 at Carnegie Mellon University. This software is freeware which rapidly generates the elaboration of 3-D graphical environments with the help of a graphic interface (http://www.alice.org/).

We used a predefined Virtual World in the ALICE library, composed of a grass surface and a blue sky. In this world, there is a camera allowing for a point of view on the world, and there is a virtual source of light that can be calibrated. In this world, we inserted a predefined ALICE object representing an insect close to the tick in its appearance: a beetle. This object shall represent our virtual tick (figure 1).

INSERT FIGURE 1

Moreover, we designed an object composed of a set of circles more or less included in each other. In the virtual space, these circles or zones represent the sensory information provided by a potential host. The spatial relationship between these circles (degree of inclusion) represent the kind of sensory information patterns that the tick can encode when faced with a potential host at one moment during one of its mental states (figure 2). The non-realistic aspect of this representation is due to the fact that the bio-mechanical dimension of behaviour is not modelled. This visual non-realism allows us to underline that affordances are composed of properties coming from the environment and not the object *per se*. The notion of object with its own identity does not exist for the tick. This is a human cognitive specificity and so, constituting an anthropomorphic point of view on the external world. We must deny this viewpoint if we want to model the *Umwelt* of an animal (Von Uexküll, 1956).

INSERT FIGURE 2

For virtual representation of the host, the larger circle corresponds to the odour and vibration information emitted by the host. These two perceptions recover the same kind of affordance for the tick, leading to dropping in both cases. On this “odour & vibration circle”, we placed a small circle representing a gripping zone, like a hair. Through this gripping surface, the tick can have access to the host during direct contact between the two animals, and afterwards move onto the gripping zone. Included in the “odour & vibration circle”, we can find the “obstacle zone”. This latter zone represents the boundaries of the host, where the tick could not go without falling, but other kinds of obstacles could be added like zones representing clothes. After this zone, you can find the “host zone”, which can be stuck to by the tick during contact and therefore allowing it to move. The following included surface is the “warm zone”, corresponding to something like critical part of the host’s skin. This zone leads the tick to try to penetrate the surface with its beak. This attempt at transformation is graphically represented as a movement down and up of the two fore legs of the tick. Two sub-zones of the “warm zone” have been defined. When the tick stands inside one of these and tries to write the term “penetrable”, the zone becomes visible. One of the penetrable zones contains blood, while the other one is without blood. If the tick finds blood, the message “blood!” appears in a bubble coming from the tick.

Now concerning the structure of the computer program, the implementation is the following (table 6):

INSERT TABLE 6

The program is embedded in a “While” loop corresponding to the reaching of the final state, that drives the modelled behaviour. The second level in this loop is composed of rules with as condition the state in which the tick stands. At the third level, we can find other rules, with as condition the patterns of sensory information encoded by the tick, that is to say the zone in which the tick is in the virtual environment (odour & vibration, host zone, warm zone, penetrable zone, blood discovered). These rules activated the set of operations required by the Turing Machine: possible transformation (penetration), change of state and action like dropping, moving, stopping, etc. Arbitrary, the tick rotation is always on the right side with an angle of 45°, and the tick always moves forward with a constant span. Note that only the elements of the Turing Machine Table have been sufficient to produce the adaptive behaviour of the virtual tick. At this level, the main modification concerns the patterns of sensory information that have been translated by virtual zones in the graphical environment.

Conclusion

The application of our method to the tick predation behaviour provides some first results which can stimulate thinking over the issues brought up by such a framework. Firstly, we see that the mental states emerging from Turing Machine analysis of the tick feeding behaviour partly differs from the behaviour stages parsed by some experts of the domain, like Wallade and Rice (1982). This means that the behavioural sequence meaningful for the observer is likely not to be those lived by the tick. But further research on these topics with specialists of the domain must be initiated.

Moreover, these 4 mental states attributed to the tick agent are logically sufficient to process 56 different patterns of relevant sensory information (or sensory invariant) which means that few mental resources in the central nervous system are sufficient to integrate the sensorial information coming from several sensorial modalities. This result supports Gibson’s ecological view of the cognition, in which higher levels of information processing in the central nervous system are considered as less important than the cognitivist approach usually assumes them to be.

If we think of the tick information processing within the framework of a cognitivist approach, we note that the Turing Machine model of the tick predation behavioural sequence suggests that the maximal cognitive resources require the integration of patterns of sensory information in working memory which should be of 2^5 bits of information during the mental state *q1*. This value is particularly low when compared to, for instance, the RAM memory capacity of actual PC computer.

In addition to a low level of central cognitive capacity required in order to perform this behavioural sequence, the Turing Machine modelling provides for very reliable behaviour in Virtual Environment. Anywhere the virtual tick is situated and goes, its behaviour is necessarily adapted to the environment. The agent encodes only the properties relevant for its behaviour and ignores the others. This reliability is possible because of the implementation of the theoretical concept that the sensory channels are in constant operation and thus able to collect patterns of sensory information. When relevant information does not perceptually exist, this lack of information is informative in itself for the animal and refers to another sensory invariant (Stoffregen, 1990). This reliability of the agent behaviour opens up some interesting perspectives in robotics, where this parameter is critical.

Another issue coming from this work resides in the implementation of a Turing Machine in a real ecological situation. It leads to the questioning of one of the basis of the Turing formalism concerning the transformation performed by the agent on the environment. The logic of our modelling leads us to take into account the necessary fact that the action of transforming the environment could prevail in an animal with regards to sensory information perception. The animal seeks to perforate the skin without first perceiving its tender or hard character. Indeed, this character of resistance is in fact contingent on the perforation power of the mouthpart and so resistance can be confirmed only by effective testing. Only the reading of the expected information will then make it possible to validate its transformation operation. Here we could qualify the sensorial information *"penetrable surface"* as a transformational invariant relative to structural invariants (*vibration, odour, gripping or sticking surface, obstacle, warm surface, blood*) (McCabe, 1982). But we think that further research on these formal issues must be realised.

Finally, this study opens some perspectives helping the model to come nearer realistic ecological behaviour and not only the affordance processing. This will consist in giving continuous values to the sensorial information according to psychophysic animal laws and continuous values to the crossing between a mental state to another. A continuous model of sensory information and internal states could better represent the behaviour sequence as embedded in a whole meaningful function which is certainly rather experienced by an agent, contrary to the artificial decomposition made by post-hoc analysis. Another realistic advance would be to connect the affordance model to a biomechanical model of the agent taking into account its sensory-motor processes. This connection between affordance processing and sensory-motor processing represents a prerequisite to model the animal learning and evolution of a virtual ecosystem (Heleno & Propero dos Santos, 1998).

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Table 1: The functional features of *I. Ricinus* tick included in our model

Morphology	***Perceptions***	***Motor program***
Head		
Roster (chelicerae)	Mechanoreceptor : Penetrable surface Gustatory receptors (blood)	Penetration, fixation (mechanical effect)
No eyes	No perception	
palpal receptors	gustatory and olfactory receptors	Penetration, fixation (mechanical effect)
Trunk		
Stomach	Blood ingested (interoceptive captors)	Form a sphere to fall to ground (mechanical effect)
Anterior legs (2)		
sensillae responding to mechanical stimuli	Mechanoreceptors: contact with surface or obstacle vibration	Grasping during questing Stopping in front of obstacle
Legs with hooks	Portability of surface	Gripping
Legs with suction cups	Portability of surface	Sticking
Forefeet with Haller's organ	olfactory chemoreceptors, gustatory receptors, mechanoreceptors (touch), and heat receptors	Dropping during questing, moving on the host

Tables 2, 3, 4 & 5 : Matching between patterns of sensory information and action scheme for each animal state (q1 to q4).

q1-questing	vibration	odour	obstacle	gripping object	sticking surface	operation
s.1	0	0	0	0	0	q1,preparing
s.2	0	0	0	0	1	q2,sticking
s.3	0	0	0	1	0	q2,gripping
s.4	0	0	1	0	0	q1,preparing
s.5	0	1	0	0	0	q2,dropping
s.6	0	0	0	1	1	q2,sticking
s.7	0	0	1	0	1	q2,sticking
s.8	0	1	0	0	1	q2,sticking
s.9	0	0	1	1	1	q2,sticking
s.10	0	1	0	1	1	q2,sticking
s.11	0	1	0	1	0	q2,gripping
s.12	0	1	1	0	0	q2,dropping
s.13	0	1	1	1	0	q2,gripping
s.14	0	1	1	0	1	q2,sticking
s.15	0	0	1	1	0	q2,gripping
s.16	0	1	1	1	1	q2,sticking
s.17	1	0	0	0	0	q2,dropping
s.18	1	0	0	0	1	q2,sticking
s.19	1	0	0	1	0	q2,gripping
s.20	1	0	1	0	0	q2,dropping
s.21	1	1	0	0	0	q2,dropping
s.22	1	0	0	1	1	q2,sticking
s.23	1	0	1	0	1	q2,sticking
s.24	1	1	0	0	1	q2,sticking
s.25	1	0	1	1	1	q2,sticking
s.26	1	1	0	1	1	q2,sticking
s.27	1	1	0	1	0	q2,gripping
s.28	1	1	1	0	0	q2,drspping
s.29	1	1	1	1	0	q2,gripping
s.30	1	1	1	0	1	q2,sticking
s.31	1	0	1	1	0	q2,gripping
s.32	1	1	1	1	1	q2,sticking

q2-exploration	odour	obstacle	gripping object	sticking surface	operation
s.33	0	0	0	0	H, dropping
s.34	0	0	0	1	H, dropping
s.35	0	0	1	0	H, dropping
s.36	0	1	0	0	H, dropping
s.37	1	0	0	0	q2,moving
s.38	0	0	1	1	H, dropping
s.39	0	1	0	1	H, dropping
s.40	1	0	0	1	q3,stopping
s.41	0	1	1	1	H, dropping
s.42	1	0	1	1	q3,stopping
s.43	1	0	1	0	q2,moving
s.44	1	1	0	0	q2,rotating
s.45	1	1	1	0	q2,rotating
s.46	1	1	0	1	q2,rotating
s.47	0	1	1	0	H, dropping
s.48	1	1	1	1	q2,rotating

q3-penetration	warm surface	penetrable surf	operation
s.49	0	0	q2,moving
s.50	0	1	q2,moving
s.51	1	0	[P],q4,stopping
s.52	1	1	q4,stopping

q4-nutrition	penetrable surf	blood	operation
s.53	0	0	q2,moving
s.54	0	1	q2, moving
s.55	1	0	q2, moving
s.56	1	1	H, dropping

Table 6: The structure of the computer program to translate the Turing Machine to a type of behaviour in Virtual Environment with the software ALICE. (Commentaries in brackets)

```
While state is not H [final state] then

  If state is q1 then
      If tick is within zone A [set of sensory information] then
      Do transformation b1
      Do action k1
      Set state to q2
      else

      If tick is within zone B [set of sensory information]  then
  else
      If state is q2 then
      etc….
```

Figure 1: The virtual tick in its Virtual Environment (ALICE software)

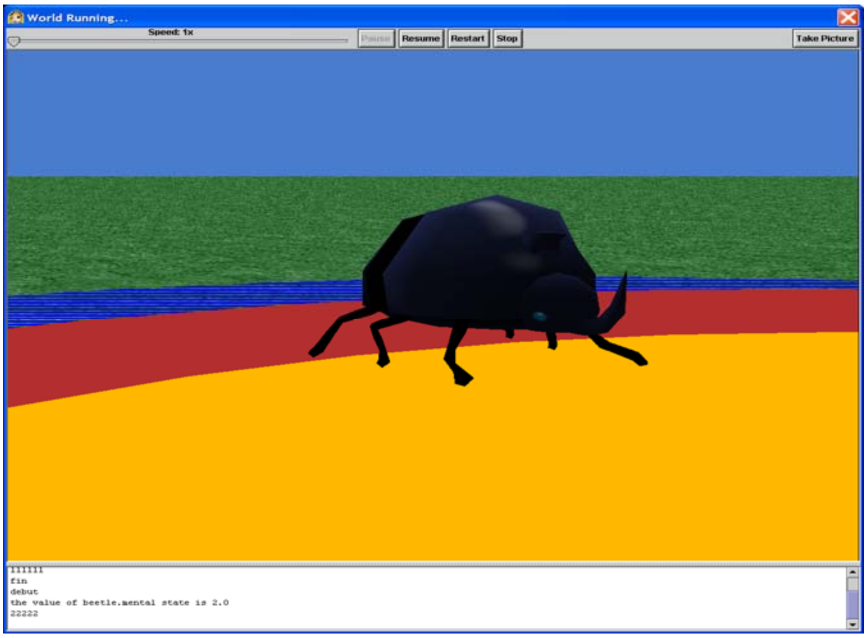

Figure 2 : Global viewpoint on the virtual host for the virtual tick, which is composed of several zones affording different kinds of sensory information patterns. In black, the tick on the host (ALICE software).